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Deriving hydro-meteorological thresholds for landslide early warning using multi-layer soil moisture information

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A key component for Landslide early warning systems (LEWS) is constituted by thresholds that provide the conditions under which landslide events can be potentially triggered. Traditionally, thresholds based on rainfall characteristics have been proposed, but recently, the hydro-meteorological approach, combining rainfall with soil moisture or catchment storage information, is increasingly gaining attention. Usually, the hydro-meteorological thresholds proposed in the literature rely on soil moisture information relating to a single layer (i.e., depth or depth range). Nevertheless, multi-layered soil moisture information can be readily provided by in-situ observations, reanalysis projects, or hydrological models. Approaches based on this multi-layered information are lacking, probably because simpler thresholds, e.g., two-dimensional, are preferred and better understood by decision makers. This study, thus, proposes a methodology, based on principal component analysis (PCA), to derive two-dimensional hydro-meteorological thresholds that use multi-layer soil moisture information. Furthermore, a piece-wise linear equation is also suggested as threshold's shape, which can be more flexible than the traditional power-law or bi-linear thresholds. Overall, results for Sicily Island (Italy), obtained using reanalysis soil moisture data at four different depths, corroborate the advantages of the hydro-meteorological approach with respect to the traditional rainfall thresholds. Specifically, a True Skill Statistic Index (TSS) equal to 0.5 is obtained for the traditional precipitation intensity-duration threshold, while a significantly higher one is obtained for the proposed hydro-meteorological thresholds using multi-layer information condensed in one variable by PCA (TSS = 0.71). Furthermore, comparing single- vs. multi-layer threshold performances provides insights on whether shallow or deep soil depth hydrological processes are more or less influent on landslide triggering. In this regard, for the analyzed study area, the multi-layer approach provides performances in terms of TSS are similar to those obtained with single-layer soil moisture at the upper depths, 0-7 cm and 7-28 cm, pointing out that landslide occurrences in Sicily are mostly driven by surface soil moisture.